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SOME PRELIMINARY DUST DEVIL MEASUREMENTS*

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ABSTRACT

The development of a mobile recording system for measuring temperature, pressure, and wind velocity in dust devils is discussed. Four dust devil penetrations are presented in which the above three quantities were measured simultaneously. All four cases show quantitatively for the first time the warm, low-pressure core of the dust devil. While the instrumentation in some cases lacked proper response and damping, the results were of sufficient accuracy to guide the development of a larger multi-level system.

1. INTRODUCTION

One of the most interesting features of arid regions during the summer is the frequent occurrence of dust devils (fig. 1). These relatively small-scale atmospheric vortices may range in size from a few inches to hundreds of feet in diameter and from a few feet to thousands of feet in height. They are a part of the general classification of atmospheric thermals in which the character of their structure is more closely related to the chimney than to the bubble type thermal.

Near the ground, the primary visible feature is the usually intense rotary motion which may be either clockwise or counterclockwise. It is believed that this rotary motion is maintained by the tendency of the air to conserve its angular momentum as it spirals in toward the dust devil's center. Superimposed on this motion is a strong vertical motion which results in a combined flow pattern similar to that of a helical vortex. There is also a radial velocity component which near the ground supplies the vortex with warm boundary-layer air and thereby acts to sustain the dust devil's vertical motion. Knowledge of these features is largely the result of visual observations of dust and other debris picked up by the dust devil as it moves along with the general environmental wind flow. (It should not be inferred that dust particle or other debris trajectories correspond to air parcel trajectories.)

At higher levels very little is known since the concentra-

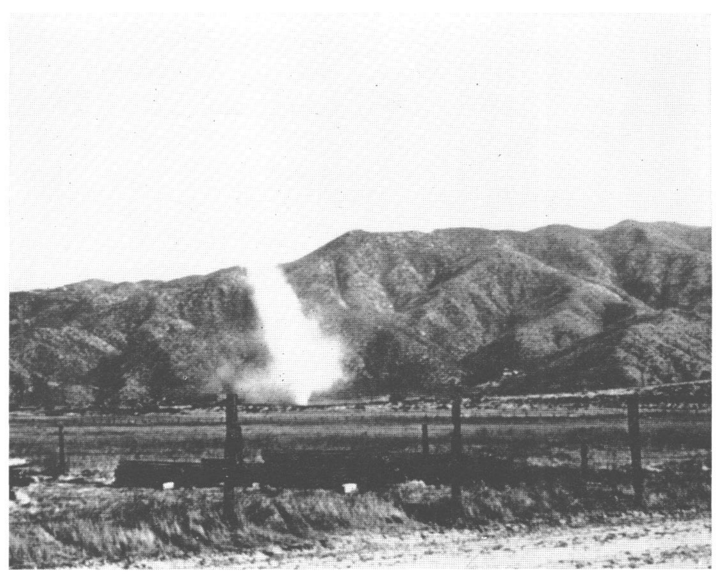

FIGURE 1.—A typical desert dust devil. The enlarged and more diffuse region just above the ground may be due to particles which have been centrifuged, because of their density, out of the main vortex.

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tion of dust and debris makes visual observations extremely difficult. Numerous sailplane flights in the upper portions of the dust devil have shown, however, that strong vertical motions may exist to very great heights. The author has made a number of flights in the upper portions of dust devils to over 15,000 ft. MSL (ground elevation approximately 2,500 ft.). The vertical motions experienced above dust devils of this size may range from a few hundred feet per minute to 2,000 ft./min., and extend over a horizontal distance of the order of a mile.

As a result of the dust devil's intensity and/or size, it may have a significant role in the heat transfer processes that take place in desert regions during the summer months. In addition, a detailed study of dust devils may lead to new knowledge of thermals in general; also new insights concerning other rotational systems such as the tornado may become apparent. To provide a firm foundation for subsequent theoretical analysis, a quantitative description based on actual measurements near and within dust devils seemed desirable. The measurement program was accomplished in two phases: (1) measurements were made of temperature, pressure, and wind velocity using off-the-shelf or very easily modified off-the-shelf equipment; (2) the results of phase 1 measurements were then used as a guide to design more sophisticated instrumentation for the study of horizontal as well as vertical variations of pressure, temperature, and wind velocity. The purpose of this paper is to discuss the instruments briefly and present the measurements of phase 1.

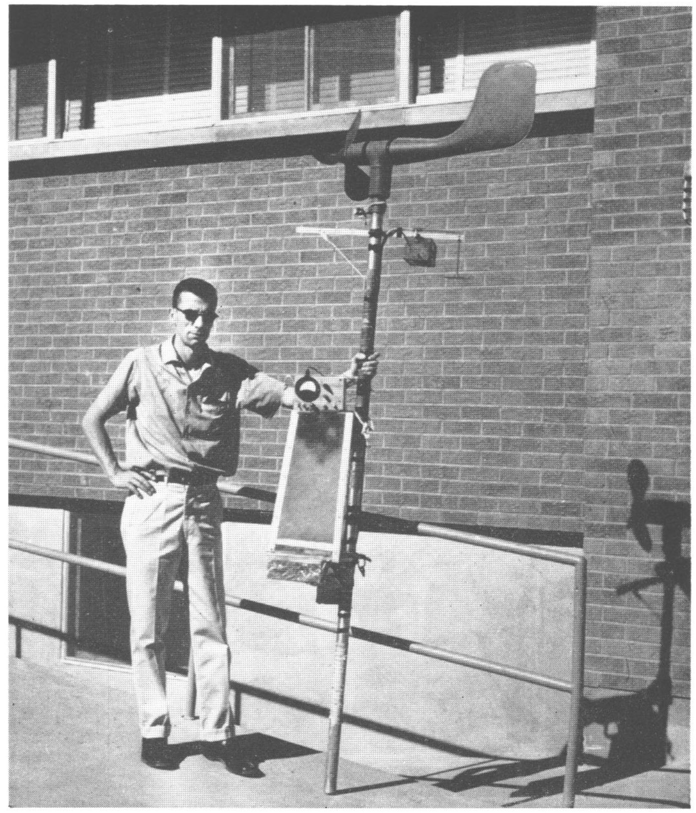

FIGURE 2.—Mobile recording system (MRS) for making dust devil measurements.

2. INSTRUMENTATION

Instruments were designed or selected with simplicity, ruggedness, mobility, and minimum construction time in mind. The primary purpose of this mobile recording system (MRS) was to obtain some insight as to the magnitude of the pressure, temperature, and horizontal wind velocity variations in some selected dust devils during the summer of 1960. The MRS (fig. 2) is built around a pole (vaulting pole) which has an extremely high strength-to-weight ratio. The entire unit weighs approximately 50 lb. and can be quickly transported by one man through the usual desert undergrowth.

The temperature sensor is mounted on a cross-bar near the top of the pole and consists of a standard-type resistance thermometer whose signal is amplified sufficiently to be displayed on a microammeter mounted in the photo box (fig. 3) near the middle of the pole. The amplifier, batteries, calibration and balancing controls, and a "slave" microammeter are mounted on top of the photo box. Prior to each dust devil penetration the temperature range selector is adjusted until the "slave" microammeter indicates the maximum usable range. The response of the temperature unit is approximately 0.5 sec. and is primarily limited by the response of the microammeter.

From the dimensions of some large dust devils and an estimate of their tangential wind velocities, the most simplified analysis yields a total pressure drop of a few millibars. For such pressure measurements, a standard aircraft altimeter was modified by the addition of a larger more sensitive aneroid unit (fig. 4). This resulted in almost a 20-fold magnification for the 100-ft. altitude needle of the altimeter; i.e., after modification one complete revolution of the 100-ft. needle corresponded to a 3.5-mb. pressure change.

To minimize the friction inherent in the pressure unit, a small electric buzzer was used as a high frequency vibrator. The frequency was such that the vibration did not affect the pressure reading during the dust devil penetration. However, the unit is sealed in a metal box and hence the heat dissipated by the buzzer acts to warm the aneroid unit causing a slight drift (0.04 mb./min.) in indicated pressure. As the sampling period is only about 20 sec., this error is not significant. There is an additional instrumental pressure drift due to the external heating of the metal box which is a result of the high desert temperatures. This error can initially be approximately 0.1 mb. per 20 sec. for an instantaneous 10° C. increase in outside air temperature and hence can also be considered insignificant during the sampling period.

Because of the relatively large aneroid mass, and deflection with pressure change, the aneroid, and hence the pressure reading, is susceptible to change in orientation of the aneroid axis or, equivalently, to angular displace-

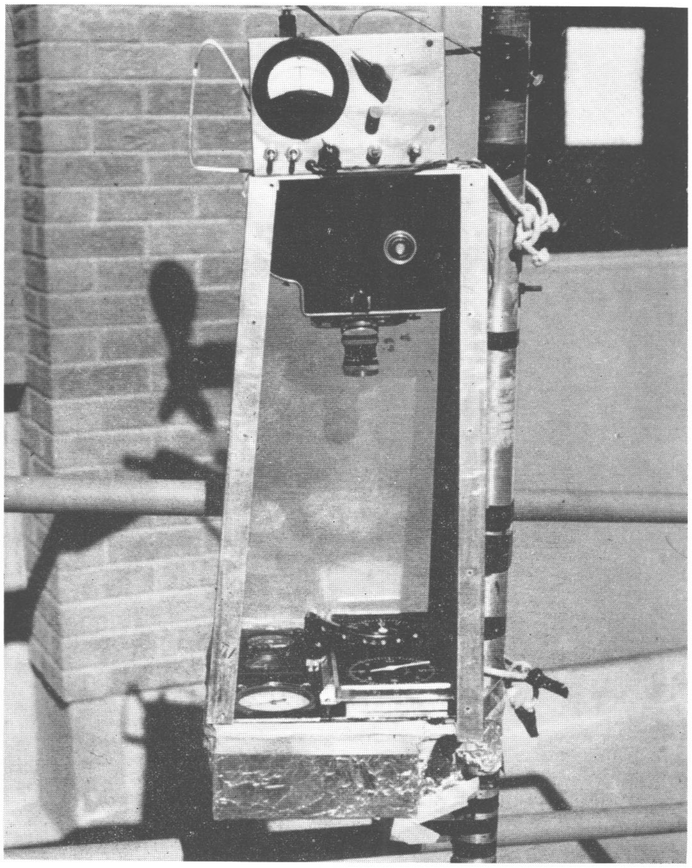

FIGURE 3.—View of photo panel and camera with photo box side removed. Temperature range selector, calibration controls, and "slave" microammeter are located above the camera.

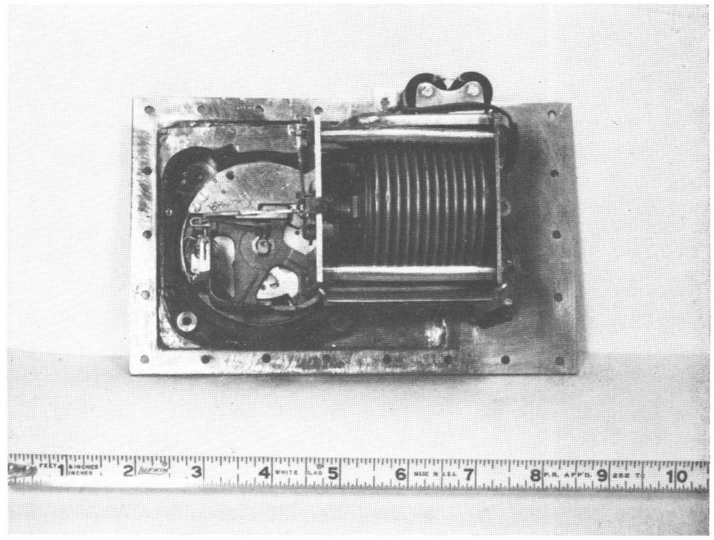

FIGURE 4.—Interior view of pressure instrument showing the aneroid connection to the modified altimeter. The vibrator is mounted on top of the aneroid.

ments from the vertical of the MRS pole. For slow or constant angular displacements of the pole the error was approximately 0.1 mb./deg. through a range of 45 degrees from the vertical. These errors were compensated for by simultaneously photographing a calibrated mercury-in-alcohol pitch-level on the photo panel. However, for oscillation frequencies near the 1-sec. time constant of the instrument, only partial compensation at most could be accomplished because of the inertia inherent in the pitch-level.

The high wind speeds near the visible dust devil vortex make the design of the pressure antenna (pressure sensing port) of critical importance. The simplest fixed static pressure antenna [1] has been suggested by Prandtl and Tietjens [2]. This design was used here and consists of a metal disk (0.125 in. thick, 4 in. diameter) supported by a narrow (0.250 in. diameter) metal tube. The disk has a 0.125-in. hole (static port) in the center which allows an air connection from the environment through the metal supporting tube to the metal box containing the modified altimeter. The pressure antenna is mounted with the static port directed downward at the end of the cross-arm near the top of the MRS (see fig. 2). The inverted position was selected for a number of reasons: (1) Smoke tests indicated that the vertical wind component at the antenna height (6.5 ft. above the ground) would probably be less than 1,000 ft. min.$^{-1}$, and hence dynamic pressure variations would be less than 0.1 mb. (2) Wind tunnel calibration tests of the antenna showed that when the static port was directed into the wind, variations of the wind with respect to the circular plate of the antenna produced a rather uniform dynamic pressure increment; however, when the static port was directed with the wind (downstream), the flow over the circular plate created a low pressure region on the static port side resulting in much larger dynamic errors whose form was complicated by subsequent flow separation. (3) With the static port opening directed downward, clogging of the narrow inlet tube by sand and other foreign particles would be minimized. For flow parallel to the metal disk and over the 0.125-in. opening, there is a small suction effect which in this case can be neglected. It has been shown to be approximately 0.01 mb. for this type of antenna in a 45 m.p.h. wind (cf. [1], p. 5).

A Bendix-Friez Windial was used to measure wind velocity (see figure 2). Prior knowledge indicated that because of the Windial's response time (both speed and direction) it was poorly suited for dust devil investigations. But lack of time necessitated use of a stock item. The wind direction and speed dials were removed from the Bendix-Friez display box and mounted horizontally on the MRS photo panel (fig. 3). The unit was converted from 115 v.a.c. to 6 v.d.c. by a simple circuit rearrangement suggested by Bendix-Friez.

The data recording was accomplished by simply photographing the instrument panel with a 16-mm. Bolex movie camera (10-mm. lens) at 32 frames per second. The photo box is completely enclosed to protect the camera and to ensure good photography. The box is covered with a semi-transparent plastic sheet which transmits sufficient light (even within the dust devil) for photo recording.

3. THE MEASUREMENTS

The field operations involved the rapid transport of the MRS by truck to the general dust devil area. The MRS was then carried by hand to a point downwind of the dust devil and placed in such a position that the dust devil would pass directly over the MRS. The results of four dust devil penetrations which occurred in the desert a few miles west of Tucson, Ariz. are shown in figures 5, 6, 7, and 8. The various scales (excluding the pressure and tilt angle) should be self-explanatory. The pressure units can be converted to millibars by use of 1 "pressure unit" $=5\times10^{-2}$ mb. The tilt angle refers to the number of degrees that the MRS was tilted away from plumb vertical and indicates where corrections have been applied and/or where the data may have a tilt angle error.

All four dust devil penetrations show the anticipated warm core, low pressure center. The temperature rise varied from almost 9° C. for the larger dust devil (fig. 5) to 3.5° C. for the smaller one (fig. 8). An interesting temperature feature of the two most intense dust devils, shown in figures 5 and 6, is that the temperature gradient is less steep in the rear than in the front of the dust devil (front refers to that portion of the dust devil which passed over the MRS first). This may be related to the difference in wind fields in these two regions but further measurements are needed before this can be determined. The dashed portion of the temperature trace in figure 7 indicates a partial loss of data as a result of a temperature range change during the dust devil penetration.

The total pressure drop (Δp) varied in the same manner from 2.3 mb. (fig. 5) for the larger dust devil to 0.6 mb. (fig. 8) for the smaller dust devil. The largest pressure drop is shown in figure 6 where $\Delta p=3.5$ mb. Because the pressure instrument is underdamped, these total pressure drops are somewhat in error due to excessive "overshooting". By impressing a continuous sinusoidal pressure oscillation on the instrument with a pressure generator it was found that at 0.5 c.p.s. the instrument had a maximum "overshoot" of 30 percent. Consequently, the pressure pulse shown in figure 6 should be reduced by about 1/3, i.e. $\Delta p=2.4$ mb. (similar corrections should be made in the other figures). For continuous correction of the pressure trace, the pressure generator data showed that smoothing the trace using a running mean of $\Delta t=0.9$ sec. resulted in a smoothed pressure trace that was a good approximation to the actual pressure trace.

Because of the relatively slow response of the Windial, the wind data are probably most accurate in the time interval preceding the passage of the dust devil center. The dust devil center is assumed to be near the pressure minimum and the closely related temperature maximum. In general, the wind speed traces show two maxima, one on either side of the low pressure center. The exception shown in figure 5 may be the result of an off-center penetration of an eccentric vortex (note that the wind direction change was only 90 degrees). In the other cases, the change in wind direction seems indicative of a center

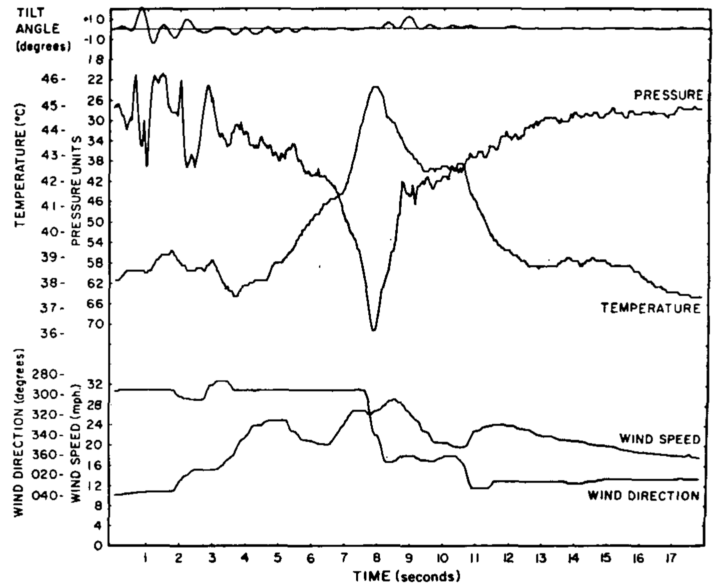

FIGURE 5.—Temperature, pressure, and horizontal wind velocity measurements through a dust devil on August 2, 1960, 1230 MST.

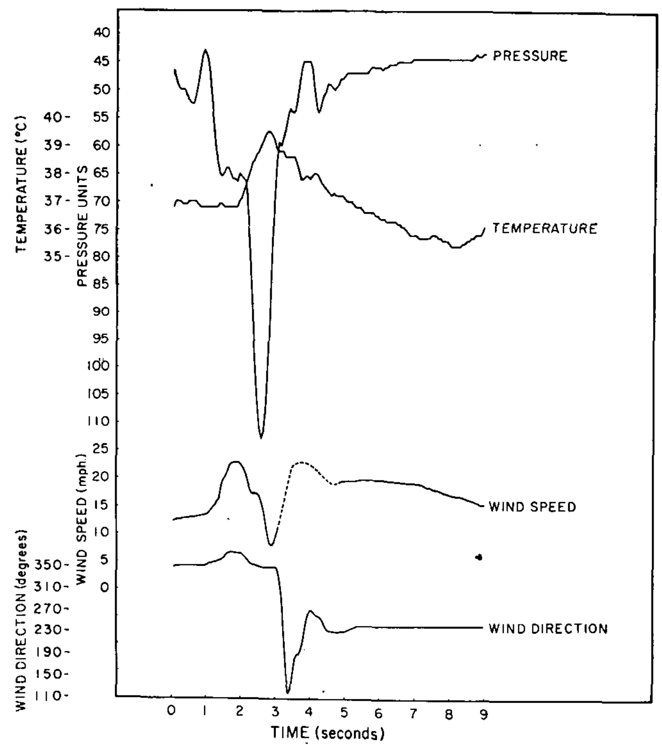

FIGURE 6.—Temperature, pressure, and horizontal wind velocity measurements through a dust devil on July 19, 1960, 1305 MST.

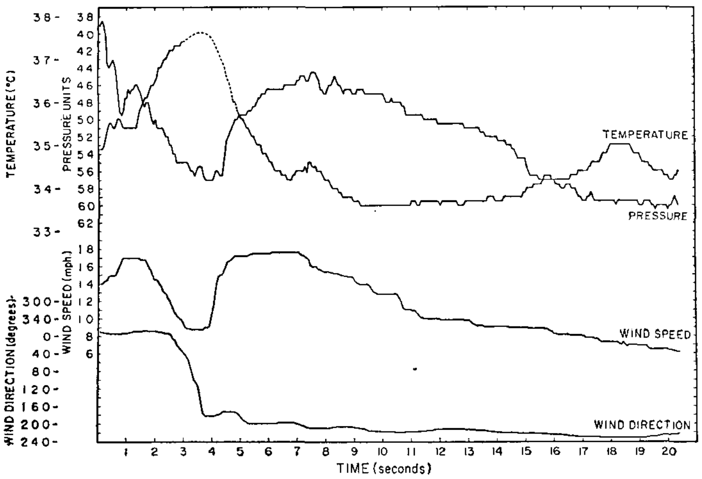

FIGURE 7.—Temperature, pressure, and horizontal wind velocity measurements through a dust devil on July 14, 1960, 1330 MST.

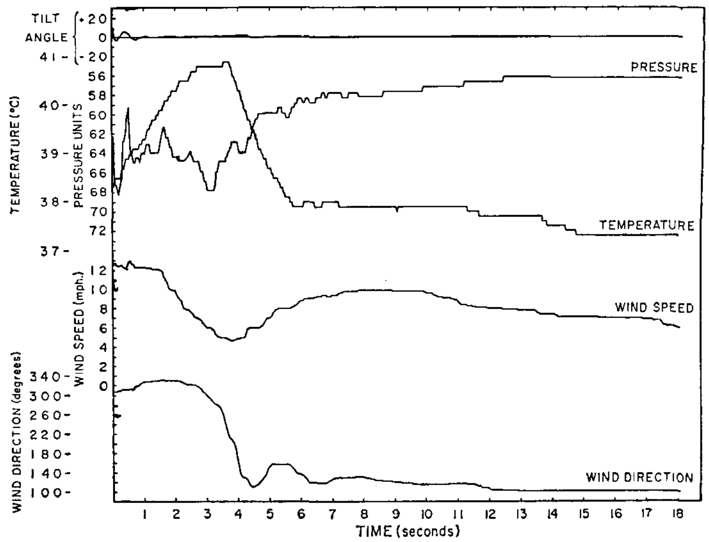

FIGURE 8.—Temperature, pressure, and horizontal wind velocity measurements through a dust devil on August 30, 1960, 1435 MST.

penetration of a concentric vortex. The dashed portion of the wind speed trace in figure 6 is the result of the slow response of the Windial. Apparently, after passing through the dust devil center, the Windial did not respond to the almost step-function change in wind direction (note the large overshoot after $t=3$ sec.), with the result that the propellor turned backwards at a rate of more than 20 m.p.h. The best estimate from the recorded data of what actually happened is represented by the dashed curve.

4. CONCLUSIONS

While the instrumentation in some cases lacked the proper response and damping, the results were of sufficient accuracy to guide the development of more sophisticated instrumentation. This was true of the quantitative results shown in figures 5–8, and equally important were the data gathered on the mobility requirements for a larger multi-level system.

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